White Paper on Multicarrier Excitation of Multipactor Breakdown: A Survey of Current Methods and Research Opportunities

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Preston T. Partridge
Antenna and Phased Array Evaluation
Antenna Systems Department

Prepared for:

National Reconnaissance Office
14675 Lee Road
Chantilly, VA 20151-1715

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Executive Summary

Multipactor breakdown is a failure mode that occurs in RF systems and system components that operate in a vacuum. For component and system verification, multipactor is treated as a peak field and voltage phenomena where the verification power level is chosen such that the maximum instantaneous operational voltage in the component is excited. In a single carrier system, this power level is fairly straightforward to determine. However, for RF components exposed to multiple distinct signals simultaneously, there are a variety of methods used to address multipactor breakdown verification.

This white paper describes methods of assessment and possibly to mitigate multipactor for spacecraft components in multiple carrier systems [1]–[3]. The methods described in this paper highlight existing approaches used in the U.S. space industry. This paper serves as a survey of current practice and is not meant to be used as a set of requirements. This document will also highlight the advantages and limitations of the various methods currently in use.

This document will also reference new analysis methods under investigation for multicarrier excitation threshold prediction based on a survey of the research literature. In general, this topic is in need of additional basic and applied research and validation in order to further improve industry understanding prior to application.

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The other members of the team came from the government and the aerospace industry. For their contributions, we thank the following contributing authors for making this collaborative effort possible:

Rick Bennett – Flight Microwave Corporation
Larry Capots – Lockheed Martin Corporation
Will Caven – Space Systems/Loral
Douglas Dawson – Jet Propulsion Laboratory
James Farrell – The Boeing Company
Bruce Flanick – Northrop Grumman
Aimee Hubble – The Aerospace Corporation
Thomas Musselman – The Boeing Company
Preston Partridge – The Aerospace Corporation
Rostislav Spektor – The Aerospace Corporation
Jeffrey Tate – Raytheon Space and Airborne Systems

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Ryan Bentley – Ball Aerospace
Larry Epp – Jet Propulsion Laboratory
Paul Giuliano – The Boeing Company
Steven Gold – Naval Research Lab
Timothy Graves – The Aerospace Corporation
Eric Holzman – Northrop Grumman
Kurt Ketola – Raytheon Space and Airborne Systems
Rolf Kich – Flight Microwave Corporation
Rami Kishek – University of Maryland
Kevin Lim – Flight Microwave Corporation
Jared Lucey – NASA GSFC
Jerry Michaelson – The Aerospace Corporation
Raul Perez – Jet Propulsion Laboratory
Stu Quade – Northrop Grumman
Joseph Roubal – Aeroflex, a Cobham Company
Norman Strampach – Lockheed Martin Corporation
Ghislain Turgeon – Space Systems/Loral
Jian Xu – Aeroflex, a Cobham Company

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1. Criteria for Evaluation of Definitions

The following criteria have been agreed upon as reasonable measures when establishing which methods to apply in a given set of analytical and/or test conditions. These criteria are by definition somewhat objective and discretion is advised in their application. The (proposed) basic criteria for establishing the applicability of a particular multi-carrier multipactor excitation method are:

- Ability to establish reasonable threshold definitions for power, transit time, and frequency of operation for the situation under investigation as appropriate to the method (e.g., P20, T20, mean frequency)

- Is the method readily amenable to analysis/test for the structure under investigation (e.g., availability of tools, simplicity of analysis…)?

- Can valid inputs be established for use of the method (e.g., number of carriers, carrier phasing, and method for carrier combination)?

- Consistency of results obtained

- Ability to understand and interpret results obtained

- Are results too restrictive or too lenient?

2. System Engineering Definitions and Guidelines

2.1 System Frequency and Power Definitions – Current Industry Practices

2.1.1 N^2P Method

2.1.1.1 Description

The N^2P method assumes that all carriers will phase such that the maximum instantaneous peak voltage is created. This peak voltage is converted to an equivalent CW power level, which is used as the verification threshold. Realizing this effective power level in the device is of extremely low probability given that generally the carriers start with random phases.

The advantage of this method is that it is understood across the industry to be a bounding condition.

2.1.1.2 Limitations

- Conservative: N^2P only occurs for an instant in time, not enough electron crossings to develop sufficient electron density

- As the number of carrier signals increases, the power thresholds grows quadratically resulting in unreasonable test configurations and potentially unattainable power levels.

2.1.2 PX/TX Methods

2.1.2.1 Description

These power definitions are based on the multipactor gap rule. In general this rule states that the power level threshold (P_X, e.g., P_4 or P_{20}) for multipactor is determined by the transit time required (T_X, T_4 or T_{20}) for an electron (bunch) to cross the structure gap. It is typically assumed that the

geometry of the structure consists of two parallel surfaces (e.g., in a parallel plate waveguide or coaxial structure). The basic formula for the transit time is provided below,

$$T_X = \frac{Xn}{2f}$$

Where X = number of gap crossings (e.g., 4 or 20), n = the multipactor order and f is the signal operating frequency. The value for the operating frequency typically used can depend on the application but is typically the mean or average frequency of the multi-carrier signals being transmitted. In some cases, according to the literature [1], the lowest frequency of the operating bandwidth is used. For the special case of equally-spaced carrier frequencies the formula for the transit time takes the form,

$$\frac{T_X}{T_e} = \frac{Xn}{2}\left(\frac{\Delta f}{f}\right)$$

Where Δf is the carrier frequency separation and T_e is the time period for the modulation envelope. The basic form of the power threshold definition is then derived by an analysis of the carrier envelope in the time domain. This determines the amount of time the envelope exceeds the desired signal power or voltage threshold. An example of this situation for a five-carrier signal is provided below in Figure 1 from Anza et al., [1]
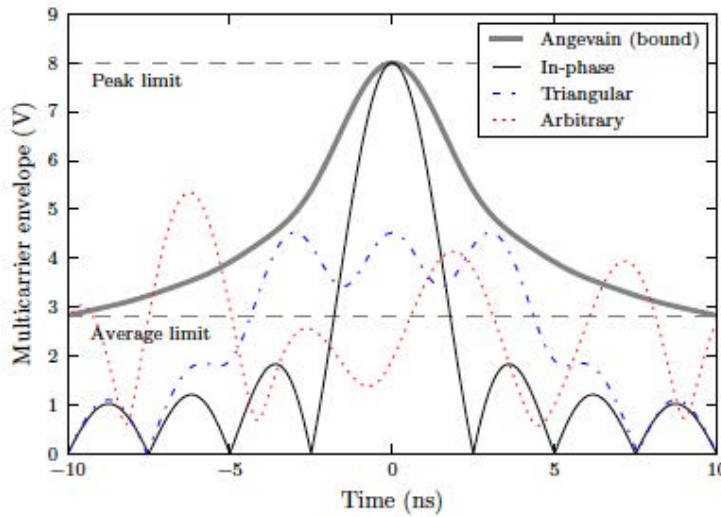

Figure 1

The threshold level for multipactor excitation is determined by aligning the peak limit line to the maximum level on the main lobe of the signal envelope. In the case above in Figure 1, the peak and average power limits are shown. The modulation envelope will of course depend on the method of combination for the carrier phases. Typically, an optimization method is used for phase combining which results in a particular modulation envelope in the time domain. Several example phase combinations are shown in Figure 1. The user will need to determine the method or algorithm for phase combination most consistent with their application. Figure 2 shows examples for a fifteen-carrier case with two different frequency separations to demonstrate this impact this parameter can have on the carrier envelope.
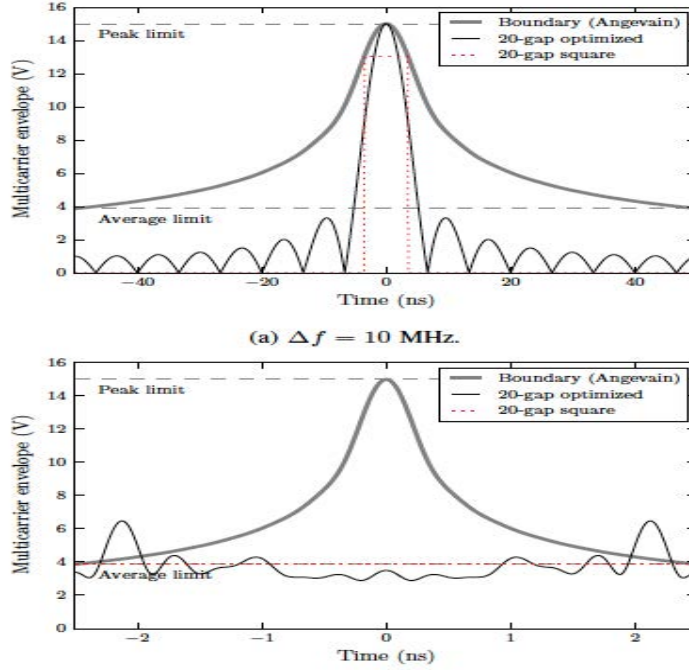
(a) $\Delta f = 10$ MHz.

Figure 2

In Figure 2, we see how the carrier separation will impact the amount of time above the signal threshold [1]. This example also demonstrates the relationship between the transit time for gap crossings and the envelope period. The magnitude of the ratio T_x/T_e from reference [1] depends on the carrier separation. This condition will determine whether the gap rule will produce a result with positive or zero multipactor margin.

The advantages of the gap crossing rules include:

- Well established method
- Defines a criterion for a single multi-carrier peak power threshold

2.1.2.2 Limitations

- Requires knowledge of the critical gap size to establish the required breakdown threshold
- These rules only consider electron growth over a single period
- They do not account for inter-period charge growth
- The results are dependent on the main lobe level of the modulation envelope (time to exceed threshold)
- The results depend on the carrier separation, leading to very conservative (extreme positive margin) or very lenient performance (zero margin) against multipactor excitation

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2.1.3   Total Average Power

2.1.3.1   Description

The total average power definition for multicarrier excitation of multipactor is based on the number of carriers N multiplied by the peak power level for each carrier P. For example, in the case of 12 carriers with 60 W peak power for each carrier the total average power threshold would be 720 W. The other parameters in the definition include,

- Frequency: worst-case in band

- Same calculation regardless of frequency band, carrier spacing, or modulation

- 3 dB multicarrier derating to account for phasing, independent of margin

The applicability of this method is covered by the following criteria

- The number of carriers is greater than or equal to 5 (N≥5)

- The carriers are assumed to be randomly phased

- This method does not necessarily apply to closely spaced channels

The advantages of this method include:

- Simple to apply and use

- Decades of heritage in its use

- Based on a statistical analysis of randomly phased peaks

2.1.3.2   Limitations

The disadvantage of this method is that it is not a fully generalized approach based on the limited guidance for carriers greater than 5. This limits the potential applicability (increases risk) for frequency plans that require a larger number of carriers.

2.2   Future Approaches and Methods

Our current understanding of the methods for analyzing multicarrier excitation of multipactor requires new research. Future work in this area is needed to address the open questions that remain about the optimal usage of existing approaches. Recommendations for such application will not be possible without new research into physical mechanisms, the impact of signal modulation design, methods for carrier phase combination as well as materials properties. In this section we outline the current efforts in some of these areas. The reader is referred to the literature for a more comprehensive review on this topic.

2.2.1   Statistical Methods

2.2.1.1   Description

For the statistical approach, the goal is to apply a mathematical method for a more realistic phase combination of the carriers in a multicarrier signal. This accounts for the statistical nature in which

phased carriers will combine in actual operation. This method is not directly or solely dependent on a transit time rule and is not limited in the number of carriers that can be considered.

The basic statistical approach involves running a large number of cases with the carrier starting phases treated as a random variable. This is similar to the development of a digital symbol sequence.

Using this method, the durations that the modulation peaks exceed a chosen threshold would determine the likelihood of multipactor excitation. The use of complex multicarrier signals with arbitrary random phase to simulate the excitation of multipactor requires proper modeling of the excitation process physics to address the statistical impact of the waveforms on electron population growth and dynamics. Research to develop these modeling approaches is still very active [1][4][7] and [8].

Advantages include:

- A realistic accounting for carrier phase combinations
- The method is based on a mathematical approach that is amenable to scientific verification
- Leads to more applicable, realistic bounding cases
- Bounding curves can be easily generated

2.2.1.2 Limitations

- Requires anchoring to an existing method where margins are not consistent (i.e., the T_x rule outlined in Section 2.1.2)
- Additional research is required in order to generalize this method for arbitrary modulation schemes and for test validation.

2.2.2 New Research in Quasi-stationary Methods

Research to increase our understanding of the impact of multicarrier signals on electron dynamics has been carried out in recent years [6]–[9]. This includes the development of a non-stationary theory to provide a more general model of the electron dynamics. Recent work also includes a framework for the analysis of multipactor excitation under non-resonant polyphase conditions. This approach works to overcome some of the limitations of earlier methods which simulate the multi-carrier signal as a single-carrier signal with a modulated pulse signal envelope. The previous method results in questions about the proper modeling of electronic charge accumulation during inter-pulse periods (pulse-off/dwell times).

Recent work in the area of quasi-stationary signal characterization has been undertaken as another alternative to the gap crossing approaches mentioned above in Section 2.1.2. These methods involve the use of a non-stationary approach to model the multipactor electron dynamics as well as characterizing the electron-surface absorption processes. Both resonant and non-resonant multipactor processes can be modeled using this technique. A key element of the new theory is to model the secondary electron velocity as a random variable. A probability distribution function (e.g., a Maxwellian distribution) is used to model the electron emission velocities during the initiation and duration of the multipactor processes. This results in a distribution of electron phases, impact energies and multipactor orders as described in Anza, et al. [8]. The new methods of Anza et al. introduce random variables for additional parameters that directly model the electron dynamics to model the physics of the multipactor process. This is distinct from solely modeling the signal characteristics of

the multipactor process by assigning only the signal phase as a random variable. Additional research (analytical and experimental) is required to determine the validity and applicability of these various approaches.

3. Risk Profile

Based on the results of a tailoring exercise and agreement from the engineering and customer communities, a risk profile should be developed that carefully outlines the impacts to the system and program based on the choice of a particular multicarrier definition. This should include an assessment of the inputs and results of the tailoring process and fully account for the impact of both advantages and disadvantages of the method chosen.

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Approved Electronically by:

Todd M. Nygren, GENERAL
MANAGER
SYSTEMS ENGINEERING
DIVISION
ENGINEERING &
TECHNOLOGY GROUP

Jacqueline M. Wyrwitzke,
PRINC DIRECTOR
MISSION ASSURANCE
SUBDIVISION
SYSTEMS ENGINEERING
DIVISION
ENGINEERING &
TECHNOLOGY GROUP

Diana M. Johnson, PRINC
DIRECTOR
COMMUNICATION SYS
IMPLEMENTATION SUBDIV
COMMUNICATIONS &
CYBER DIVISION
ENGINEERING &
TECHNOLOGY GROUP

Jackie M. Webb-Larkin,
SECURITY SPECIALIST III
GOVERNMENT SECURITY
SECURITY OPERATIONS
OPERATIONS & SUPPORT
GROUP

Technical Peer Review Performed by:

Jacqueline M. Wyrwitzke,
PRINC DIRECTOR
MISSION ASSURANCE
SUBDIVISION
SYSTEMS ENGINEERING
DIVISION
ENGINEERING &
TECHNOLOGY GROUP

Preston Partridge, ENGRG
SPECIALIST
ANTENNA & PHASED
ARRAY EVALUATION
ANTENNA SYSTEMS DEPT
ENGINEERING &
TECHNOLOGY GROUP

Cheryl L. Sakaizawa,
ADMINISTRATIVE SPEC III
MISSION ASSURANCE
SUBDIVISION
SYSTEMS ENGINEERING
DIVISION
ENGINEERING &
TECHNOLOGY GROUP

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Craig Wesser
Northrop Gruman
craig.wesser@ngc.com

Richard Bennett
Flight Microwave
bennett@flightmw.com

Larry Capots
Lockheed Martin
larry.capots@lmco.com

Richard Fink
NRO
finkrich@nro.mil

Dennis Boiter
Intelsat
Dennis.Boiter@intelsatgeneral.com

Steve Carlson
Cadence
carlson@cadence.com

Marvin LeBlanc
NOAA
Marvin.LeBlanc@noaa.gov

Silva Bouchard
Northrop Grumman
Silvia.Bouchard@ngc.com

Danny Chan
Raytheon
danny_s_chan@raytheon.com

Robert Adkisson
Boeing
robert.w.adkisson@boeing.com

Mark Braun
Raytheon
mark.j.braun@raytheon.com

Janica Cheney
ATK
janica.cheney@jtk.com

Mark Baldwin
Raytheon
Mark.L.Baldwin@raytheon.com

Marvin Candee
Lockheed Martin
marvin.candee@lmco.com

Kevin Chisholm
United Technologies, ISR Systems
Kevin.Chisholm@utas.com

David Davis SMC/EN David.Davis.3@us.af.mil	Sherri Fike Ball sfike@ball.com	Mohinder Guru Intelsat Mohinder.Guru@intelsat.com
Ken Dodson SSL ken.dodson@sslmda.com	Bruce Flanick Northrop Grumman bruce.flanick@ngc.com	Tom Hanhauser Lockheed Martin Thomas.j.hanhauser@lmco.com
Deanna Doner Lockheed Martin deanna.e.doner@lmco.com	Will Caven SSL will.caven@sslmda.com	Bill Hansen Lockheed Martin bill.hansen@lmco.com
Jason Emery Raytheon Brent.Emery@raytheon.com	Helen Gjerde Lockheed Martin helen.gjerde@lmco.com	John Harrington Boeing jack.harrington@boeing.com
Dave Erstad Honeywell dave.erstad@honeywell.com	Steven Gold Naval Research Lab steven.gold@nrl.navy.mil	Keith Henderlong MIT Lincoln Labs Keith.Henderlong.ffrdc@mda.mil
James Farrell Boeing james.t.farrell@boeing.com	Claude Goldsmith Lockheed Martin claude.goldsmith@lmco.com	Mike Herzog Pacific Scientific mherzog@psemc.com
James Fieber Lockheed Martin James.r.fieber@lmco.com	Jonathan Graf MacAulay-Brown, Inc. jonathan.graf@macb.com	Bill Hoehn Raytheon wkhoehn@raytheon.com

Jerry Holsomback
Raytheon
jerry.b.holsomback@raytheon.com

Kurt Ketola
Raytheon
ketola@raytheon.com

Jim Larosa
BAE Systems
james.larosa@baesystems.com

Eric Holzman
Northrop Grumman
eric.holzman@ngc.com

Rolf Kich
FMC
kich@flightmw.com

Neil Limpanukorn
SSL
Neil.Limpanukorn@sslmda.com

Paul Hopkins
Lockheed Martin
paul.c.hopkins@lmco.com

Mark King
Micropac
markking@micropac.com

Louie Lombardo
Lockheed Martin
louie.lombardo@lmco.com

Daniel Hyatt
MDA
Daniel.Hyatt@mda.mil

Brian Kosinski
SSL
Brian.Kosinski@sslmda.com

Rob Lyon
SSL
robert.lyon@sslmda.com

Ed Jopson
Northrop Grumman
edward.jopson@ngc.com

John Kowalchik
Lockheed Martin
John.J.Kowalchik@lmco.com

Ronand Mandel
Lockheed Martin
ronald.h.mandel@lmco.com

Frederick Kelso
MDA
Frederick.Kelso@mda.mil

Debbie Schreiber
Lockheed Martin
debbie.schreiber@lmco.com

Patrick Martin
NASA
partick.martin@nasa.gov

Jeanne Kerr
Lockheed Martin
Jeanne.R.Kerr@lmco.com

C. J. Land
Harris
cland@harris.com

Steven McNeil
Xilinx
stevem@xilinx.com

Kevin Meadows Northrop Grumman kevin.meadows@ngc.com	Jeff Oberst Lockheed Martin jeff.oberst@lmco.com	Robert Ricco Northrop Grumman bob.ricco@ngc.com
Eli Minson Ball eminson@ball.com	Frank Pastizzo SSL frank.pastizzo@sslmda.com	John Robinson Aerojet Rocketdyne john.robinson@rocket.com
Tom Musselman Boeing thomas.e.musselman@boeing.com	Kevin Paxton Boeing kevin.r.paxton@boeing.com	Frank Roller Lockheed Martin frank.d.roller@lmco.com
Helen Narciso Lockheed Martin helen.narciso@lmco.com	David Pinkley Ball dpinkley@ball.com	Joseph Roubal Aeroflex, a Cobham Company joseph.roubal@aeroflex.com
John Nelson Lockheed Martin john.d.nelson@lmco.com	Rob Pollard Ball rpollard@ball.com	Rabindra Singh SSL Rob.Singh@sslmda.com
David Newton Northrop Grumman david.a.newton@ngc.com	Anne Ramsey Harris aramsey@harris.com	Melanie Sloane Lockheed Martin melanie.sloane@lmco.com
Ethan Nguyen Raytheon ethan_m_nguyen@raytheon.com	Brian Reilly DCMA Brian.Reilly@dmca.mil	Homer D. Stevens Lockheed Martin homer.d.stevens@lmco.com

Norman Strampach Lockheed Martin norman.strampach@lmco.com	Ghislain Turgeon SSL Ghislain.Turgeon@sslmda.com	Hal Bell NASA harold.m.bell@nasa.gov
David Swanson Orbital ATK David.Swanson@orbitalatk.com	Deborah Valley MIT Lincoln Labs deborah.valley@ll.mit.edu	Mike Wadzinski MDA mike.wadzinski@mda.mil
Alfred Tadros SSL Alfred.Tadros@sslmda.com	Richard Veres Honeywell richard.veres@honewell.com	Brig Gen Anthony Cotton NRO cottonan@nro.mil
Jeffrey Tate Raytheon jeffrey_tate@raytheon.com	Brynn Watson Lockheed Martin brynn.a.watson@lmco.com	Douglas Dawson NASA - JPL douglas.e.dawson@jpl.nasa.gov
Paul Thompson Intelsat PaulAlex.Thompson@intelsat.com	Lance Werthman Lockheed Martin lance.werthman@lmco.com	Ryan Bentley Ball rbentley@ball.com
Brett Tobey Lockheed Martin brett.f.tobey@lmco.com	Dan Yasukawa Lockheed Martin dan.yasukawa@lmco.com	Rami Kishek University of Maryland ramiak@umd.edu
Mike Tolmasoff Boeing mike.w.tolmasoff@boeing.com	Thomas Fitzgerald SMC thomas.fitzgerald.5@us.as.mil	Kevin Lim Flight Microwave Corporation lim@flightmw.com

Jared Lucey
NASA
jared.f.lucey@nasa.gov

Jian Xu
Aeroflex, a Cobham
Company
jian.xu@aeroflex.com

APPROVED BY_____   DATE_____
(AF OFFICE)